

NASA's Robotic Mining Competition Provides Undergraduates Full Life Cycle Systems Engineering Experience

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Abstract. NASA has held an annual robotic mining competition for teams of university/college students since 2010. This competition is yearlong, suitable for a senior university engineering capstone project. It encompasses the full project life cycle from ideation of a robot design, through tele-operation of the robot collecting regolith in simulated Mars conditions, to disposal of the robot systems after the competition. A major required element for this competition is a Systems Engineering Paper in which each team describes the systems engineering approaches used on their project. The score for the Systems Engineering Paper contributes 25% towards the team's score for the competition's grand prize. The required use of systems engineering on the project by this competition introduces the students to an intense practical application of systems engineering throughout a full project life cycle.

Introduction

This paper will introduce the NASA Robotic Mining Competition (RMC), explaining how it works and the role systems engineering plays in it. The Systems Engineering Paper, a required scoring element for each team to be eligible to compete in the arena with the team's robot, is then described along with the judging rubric (provided to the student teams), the judging process, and award winners from previous competitions. Student and faculty support provided by NASA for use of systems engineering on the project will be discussed. The paper will conclude with a summary and discussion of how successful this competition has been in getting undergraduate students to actually practice systems engineering throughout the complete life cycle of their robot.

The NASA Robotic Mining Competition

Recent discoveries by NASA missions to Mars, such as the Mars Science Laboratory rover named "Curiosity" and instruments on orbiting satellites, have found large amounts of water in the form of water ice at the higher latitudes and also hydrated minerals globally on Mars. These sources of water on Mars are the result of ancient clays and clay-like minerals called phyllosilicates, or other poly-hydrated sulfates that formed millions of years ago in wet environments on the surface or underground. Capturing this water is key to allow humans to "live off the land." This is referred to as in-situ resource utilization (ISRU). The water can be used for human consumption, hygiene, to make rocket propellant for the journey home, to grow plants, to provide radiation shielding, and can be used in various manufacturing processes.

Before the water can be used in a human Mars station, the granular minerals which contain the water must be mined, or the soil overburden must be removed, to expose the water ice. The minerals and soil are typically in the form of crushed and weathered rock called “regolith.”

The NASA Robotic Mining Competition is for university-level students to design and build a mining robot that can traverse simulated Martian terrain. The mining robot must then excavate the regolith simulant and/or the ice simulant (represented by gravel) and return the excavated mass for deposit into the collector bin to simulate an off-world, in situ resource mining mission. Figure 1 shows the robots for two teams setting up for the competition in the arena.



Figure 1. Two robots preparing to excavate simulated Martian regolith in 2016.

The complexities of the challenge include the abrasive characteristics of the regolith simulant, the weight and size limitations of the mining robot and the ability to tele-operate it from a remote Mission Control Center. Note in figure 1 that the pit supervisors and student team members are in full hazmat suits, exposure to even simulated Martian regolith can be unhealthy. Figure 2 shows students in the remote control center operating their robots over in the competition arena.

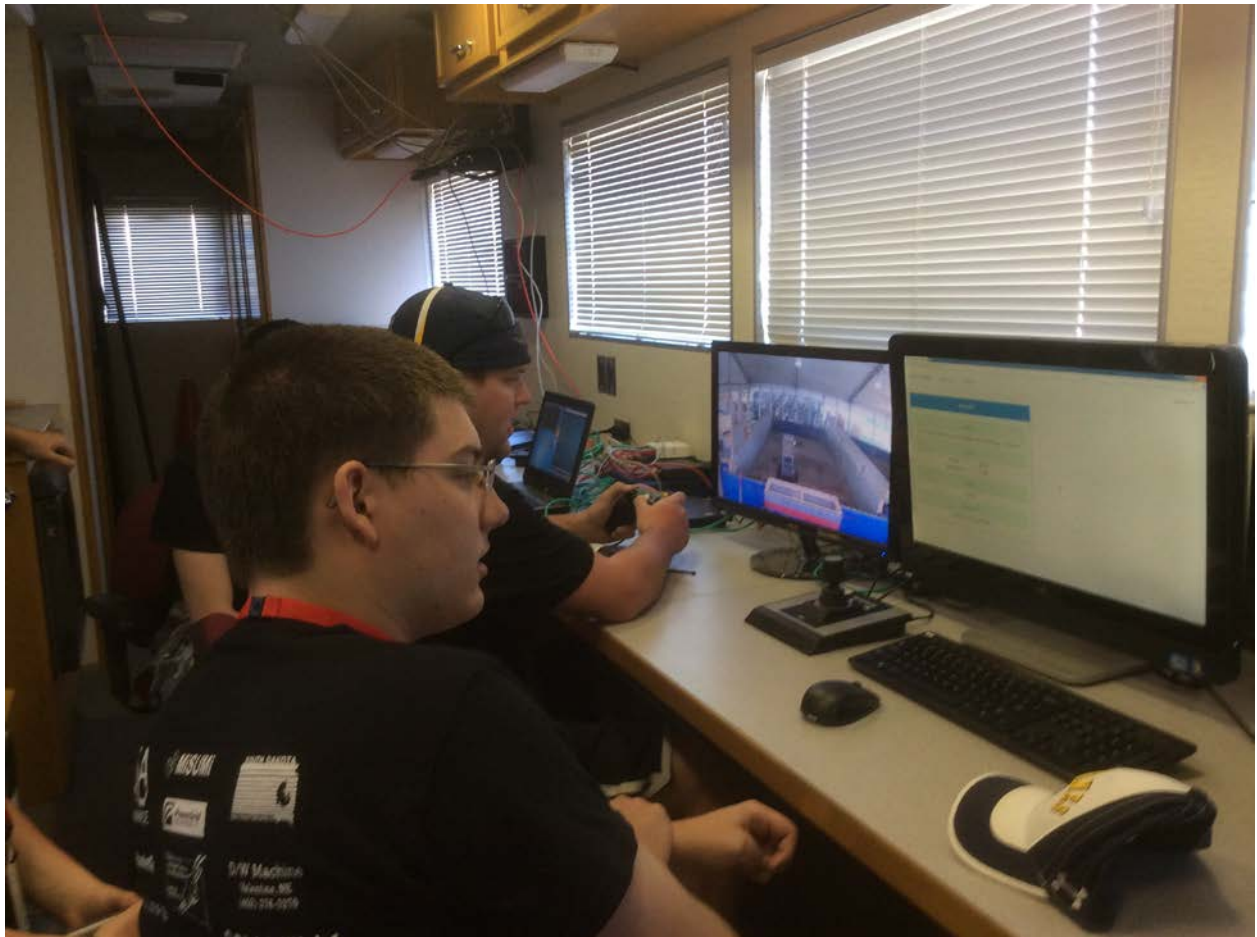


Figure 2. Students operating their robots remotely from Mission Control.

The on-site mining portion of the competition requires teams to consider a number of design and operation factors such as dust tolerance and dust projection, communications, vehicle mass, energy/power required and autonomy. In addition to the on-site mining category, teams must also submit a systems engineering paper that explains their design philosophy and the systems engineering processes they used on their project. The teams also get extra points for engaging in social media and public engagement throughout the year, and have the option of giving a presentation to judges while at Kennedy Space Center. Points from both the mandatory and optional categories are tallied for the grand prize, the Joe Kosmo Award for Excellence.

NASA benefits from the competition by encouraging the development of innovative robotic excavation concepts from student teams, which may result in clever ideas that could be applied to an actual excavation device, and/or payload on an ISRU mission. Advances in Martian mining have the potential to significantly contribute to human spaceflight and NASA space exploration operations.

Details of this competition can be found online at <https://www.nasa.gov/nasarmc>

The NASA RMC got its start in 2010 as the NASA Lunabotics Competition (Guerra, Murphy, May 2013). In 2011, the competition was open to undergraduate and graduate student teams enrolled in colleges or universities worldwide. Table 1 lists the countries of teams that have participated in Lunabotics/RMC. In 2014, due to NASA budgetary constraints, participation was limited to teams from colleges or universities located in the United States, its Commonwealths, Territories and/or possessions.

Table 1: Participating Countries in Lunabotics/RMC

Competition Year	Team Countries
2010 Lunabotics	USA
2011 Lunabotics	USA, Bangladesh, Canada, Colombia, India, Spain
2012 Lunabotics	USA, Bangladesh, Canada, Colombia, India, Mexico, Romania, South Korea
2013 Lunabotics	USA, Australia, Bangladesh, Canada, Colombia, India, Mexico, Poland
2014 – 2017 RMC	USA

The focus originally for Lunabotics was on teams of students designing, building, and remotely operating robots which excavate and collect (simulated) lunar regolith. In recent years, with the discovery of water sources on Mars, NASA's focus for this competition turned towards Mars, and the competition was renamed. The Systems Engineering Paper and the mining components have been required elements of the competition since the beginning in 2010.

Student Teams

The NASA RMC registers approximately 50 student teams each year. Since its inception, the RMC has hosted over 300 different robot teams and 3,000 students from across the United States, including Alaska, Hawaii, and the Commonwealth of Puerto Rico. 50 teams are about the maximum that logistics will allow to compete in the arena during one week. Typically, of the 50 student teams that are accepted in the fall, 43 or more make it to the on-site competition and compete in the arena in May. Each team must have at least two undergraduate students, and all students on the team must be enrolled at their sponsoring institution the previous or current semester at the time of the on-site competition. The teams range in size from two students to upwards of 30 students. Since 2010, undergraduate students have been in a majority in all teams. The team must include a faculty member/advisor employed with the institution during the competition.

Because of the mining and robotics nature of this competition, it tends to draw teams and faculty advisors from departments other than aerospace engineering departments. Aerospace engineering is a field with a long history of use of systems engineering, and systems engineering is often incorporated in undergraduate programs. For example, systems engineering plays a major role in the aeronautical senior capstone project offered at the University of Texas at Austin in the Aerospace Engineering department (Chaput 2016). Likewise, systems engineering plays a major role in the aerospace senior capstone project offered at Texas A&M University (Valasek and Shryock 2015). The majority of the RMC teams historically have been dominated by engineering and computer/IT students, however, many teams include members outside of engineering and the physical sciences. From years of discussions with students and faculty members for the teams, the NASA RMC is often these students' first and only introduction to systems engineering concepts. The exposure to systems engineering concepts that the RMC provides will likely be carried productively with them in their careers into industries not traditionally known for use of systems engineering. As can be seen in the next section, the major

sponsors of the NASA RMC would naturally have an interest in hiring graduates from the dominating traditional engineering disciplines in the teams.

Sponsors

The NASA RMC enjoys rather broad industry sponsorship, with Caterpillar, Inc. being the major sponsor (besides NASA). Caterpillar, Inc. has exhibited a strong interest in robotics, especially autonomous robotics, and sponsors the competition's Autonomy Award. Table 2 lists major sponsors of the RMC since 2011. The levels of sponsorship reflect relative levels of financial and other support.

Table 2: NASA RMC Industrial Sponsors

2016 Sponsors	
Stellar Sponsor:	Caterpillar, Inc.
Bronze Sponsor:	Boeing, Harris Corporation, Moon Express
Copper Sponsor:	Honeybee Robotics, Space Florida
Other Contributors:	Astronauts Memorial Foundation, Kennedy Space Center Visitor Complex, Secor Strategies, LLC, Atlantis Education,
2015 Sponsors	
Stellar Sponsor:	Caterpillar, Inc.
Bronze Sponsors:	Harris Corporation, Honeybee Robotics Corporation, Lockheed Martin, Moon Express, Inc.
Copper Sponsor:	igus, inc., Space Florida
2014 Sponsors	
Stellar Sponsor:	Caterpillar, Inc.
Silver Sponsor:	National Instruments
Bronze Sponsors:	Harris Corporation, Honeybee Robotics Corporation, igus, inc., Moon Express, Inc., South African Space Resources Association (SASRA), Solar System Exploration Research, Virtual Institute (SSERVI), Space Florida
Copper Sponsor:	American Society of Civil Engineers (ASCE), Lockheed Martin, Ocean Potion
Other Contributors:	Delaware North Companies Parks and Resorts, Secor Strategies, LLC
2013 Sponsors	
Lunar Sponsor:	Caterpillar, Inc.
Silver Sponsor:	National Instruments
Bronze Sponsors:	Harris Corporation, Honeybee Robotics Corporation, igus, inc., MacDonald, Dettwiler and Associates (MDA) Corporation, Moon Express, Inc., Ontario Drive & Gear / Argo, South African Space Resources Association (SASRA), NASA Lunar Science Institute (NLSI), SpaceX, The LEGO Group
Copper Sponsor:	AIAA Space Resources, Ocean Potion, XPRIZE Foundation, Inc.
Other Contributors:	Delaware North Companies Parks and Resorts, Secor Strategies, LLC
2012 Sponsors	
Lunar Sponsor:	Caterpillar, Inc.
Gold Sponsor:	Newmont Mining Corporation
Bronze Sponsors:	Harris Corporation, igus, inc., Ontario Drive & Gear / Argo, South African Space Resources Association (SASRA), NASA Lunar Science Institute (NLSI), SpaceX, The LEGO Group, United Space Alliance
Copper Sponsors:	AIAA Space Resources Technical Committee, American Society of Civil Engineers (ASCE), Honeybee Robotics Corporation, The Google Lunar X PRIZE/MoonBots Challenge Program
Other Contributors:	Delaware North Companies Parks and Resorts, Secor Strategies, LLC
2011 Sponsors	
Platinum Sponsor:	Caterpillar, Inc.
Gold Sponsor:	Newmont Mining Corporation
Bronze Sponsors:	Honeybee Robotics Corporation, Harris Corporation, NASA Lunar Science Institute (NLSI)
Copper Sponsors:	The LEGO Group, Delaware North Companies Parks and Resorts

Role of Systems Engineering in the RMC

Robotic operations on Mars pose many difficult and novel challenges not experienced on Earth. This has been recognized widely, and was featured in the popular television show “The Big Bang Theory.” In one episode (“The Big Bang Theory,” “The Lizard-Spock Expansion” 2008), character Howard Wolowitz, showing off to a new girlfriend, without permission, accidentally got a Mars rover stuck. The attempt to free it uncovered evidence of life on Mars, for which Howard could not claim credit.

Developing systems to meet such novel challenges requires a heavy dose of the systems engineering discipline. As a result, NASA requires that RMC teams demonstrate how they employed systems engineering in the development of their robotic mining system. For evidence of the use of systems engineering, NASA requires that each team produce a paper that describes how they applied systems engineering in development of their robot. Awards for first through third place, and potentially additional judge’s awards, may be awarded for the best Systems Engineering Papers. Many of the sponsors of the RMC that are not traditionally considered systems engineering powerhouses pay close attention to the Systems Engineering Paper awards, and often interview students at the RMC competition.

Awards

The NASA RMC has numerous awards, with the most prestigious being the grand prize, The Joe Kosmo Award of Excellence. The Joe Kosmo Award of Excellence is comprised of scores from the five competition events: On-Site Mining competition (25%), the Systems Engineering Paper (25%), the Outreach Project Report (20%), the Slide Presentation and Demonstration (20%), and Social Media and Public Engagement (10%). The first three events are mandatory components, and the latter two are optional. Table 3 lists the awards that may be presented at the competition final banquet.

Table 3: NASA RMC Awards

THE JOE KOSMO AWARD FOR EXCELLENCE	Awarded to the team that scores the most points in the five competition events.
Systems Engineering Paper (mandatory event)	Awarded to the team that best discusses the Systems Engineering methods used to design and build their mining robot. The paper is evaluated by support and operations personnel from across NASA.
Robotic On-Site Mining (mandatory event)	Awarded to the team that: passes robot and communication inspections, mines more than 10 kg of regolith, most efficiently uses bandwidth, minimizes robot mass, reports energy consumed, has a dust tolerant design & performs dust free operations, performs tele-robotically and/or autonomously, and mines the most resources.
Outreach Project Report (mandatory event)	Awarded to the team with the best educational outreach project in their local community to engage students in STEM (Science, Technology, Engineering and Math). Outreach activities should capitalize on the excitement of NASA's discoveries to spark student (K-12) interest and involvement in STEM.
Slide Presentation and Demonstration (optional event)	Awarded to the team that best presents their project at the competition in front of an audience including NASA and private industry judges.
Social Media and Public Engagement (optional event)	Awarded to the team that uses various social media platforms to engage the public in their participation with the RMC and engages with NASA and other robotics teams.
The Judge's Innovation Award	Awarded to the team that demonstrates the most innovative design.
The Caterpillar Autonomy Award	Awarded to the teams with the first, second and third most autonomous points averaged from both mining attempts, even if no regolith is deposited. In the event of a tie, the team that deposits the most regolith will win. If no regolith is deposited, the Mining Judges will choose the winner.
The Regolith Mechanics Award	Awarded to the team with the best example of a real granular innovation that identified a specific regolith mechanics problem (like the way the soil flows around the grousers, or angle of repose too high in their dump bucket, etc.) and intentionally improved their design to deal with it. Courtesy of the Center for Lunar and Asteroid Surface Science (CLASS), part of NASA's Solar System Exploration Research Virtual Institute (SSERVI) Network.
The Efficient Use of Communications Power Award	Awarded to the team for using the lowest average data utilization bandwidth per regolith points earned in both the timed and NASA monitored portion of the competition. Teams MUST collect the minimum amount of regolith to qualify for this award.

The RMC Systems Engineering Paper

The RMC Systems Engineering paper is a required element for a team to be eligible for any awards, and is an award in its own right. The purpose of the Systems Engineering Paper is for the teams to demonstrate how they used systems engineering processes while designing, building, and testing their robot system. A minimum score of 20 out of 25 possible points must be achieved to qualify to win in this category.

Rubric

A scoring rubric is provided to the student teams at the beginning of the RMC year, and is used by the Systems Engineering Paper judges throughout the judging process. This rubric provides requirements not unlike those found in a NASA Request for Proposal. There are three primary elements (Content, Intrinsic Merit, and Technical Merit) that are scored in the Systems Engineering Paper.

In the following discussion of the primary elements for judging, a few examples from each element are provided from a variety of recent RMC Systems Engineering Papers to illustrate the level of sophistication and excellence that the student teams are demonstrating in their use of systems engineering on their projects.

Element I, Content: This element primarily defines the professional formatting for the paper, demonstrates evidence of sponsoring faculty advisor review and approval, and requires a Purpose Statement related to the application of systems engineering on the RMC project. This element provides up to three points in the overall paper scoring. The paper is limited by this element to 20 pages with an additional five appendix pages.

The most important systems engineering aspect of the Content Element is the Purpose Statement, and it should appear very early in the Systems Engineering Paper. The Purpose Statement demonstrates that the team understands why they should use systems engineering in their project, and what they hope to achieve by using it. A good example follows of the type of Purpose Statement that assures the judges that the team understands why they need to use systems engineering.

“The aim of the team has been to develop a simple design which could successfully compete in the competition as well as serve as a proof-of-concept for potential future interplanetary NASA mining missions. This paper will summarize the goals of the Oakton Robotics mining robot project and encapsulate the engineering design process the team utilized to accomplish these goals, as per the systems engineering process outlined by NASA.”
(Mahmood, M. 2016)

Element II, Intrinsic Merit: This element is more focused on the overall management of the RMC project. The required topics to be addressed are schedule and schedule management, cost budgeting and cost management, the design philosophy driving the use of systems engineering, and demonstration that at least three major technical maturity reviews were employed in the development of the project. This element provides up to eight points in the overall paper scoring.

The teams should demonstrate use of a schedule and budget management throughout the project. Typically a Gantt chart showing the schedule with milestones for the three required reviews is a minimum the judges expect to see. Figure 3 is an example of an RMC schedule that demonstrates good schedule planning and management, with the major reviews called out as major milestones.

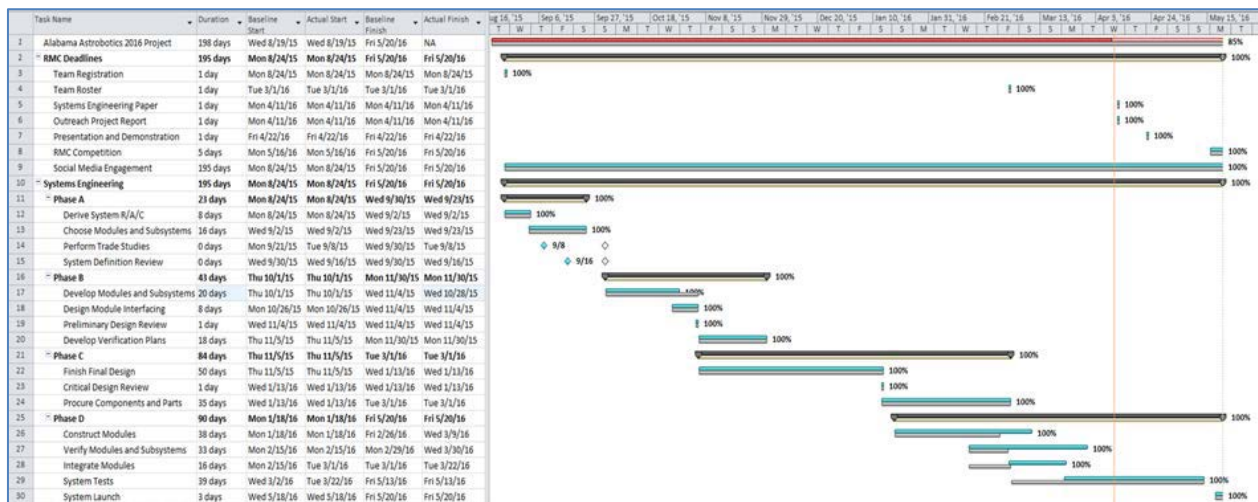


Figure 3: The 2016 University of Alabama RMC Systems Engineering Paper schedule clearly delineates all major activities as well as the three required reviews. (The University of Alabama in collaboration with Shelton State Community College, 2016)

The Design Philosophy is also an important systems engineering element because it gives purpose to the project and should be reflected in the paper's discussion of the Technical Merit Elements. The following is a good example of a Design Philosophy that a team carried throughout the Systems Engineering Paper.

"The intention of the 2016 UNC Charlotte 49er Miners team is to enhance the already constructed excavator from the previous year while developing and implementing a complete autonomous system to be used. This will encompass the design of a new dumping method to get more of the regolith in the collector bin, a new localizer, and navigation system. Due to the amount of regolith and icy simulant that was collected last year, this year's team's main aspiration for the project in the Systems Engineering field is to have the robot run fully autonomously." (Charlotte 49er Miner Robotics, 2016)

How a team discusses the major design reviews is also a critical Intrinsic Merit element. The 2016 team Illinois Robotics in Space (IRIS) from the University of Illinois at Urbana-Champaign captured a mature understanding of how well-conducted design reviews contribute to a successful system in one of the graphics in their Systems Engineering Paper (Illinois Robotics in Space (IRIS), University of Illinois at Urbana-Champaign, 2016) and is presented in figure 4.

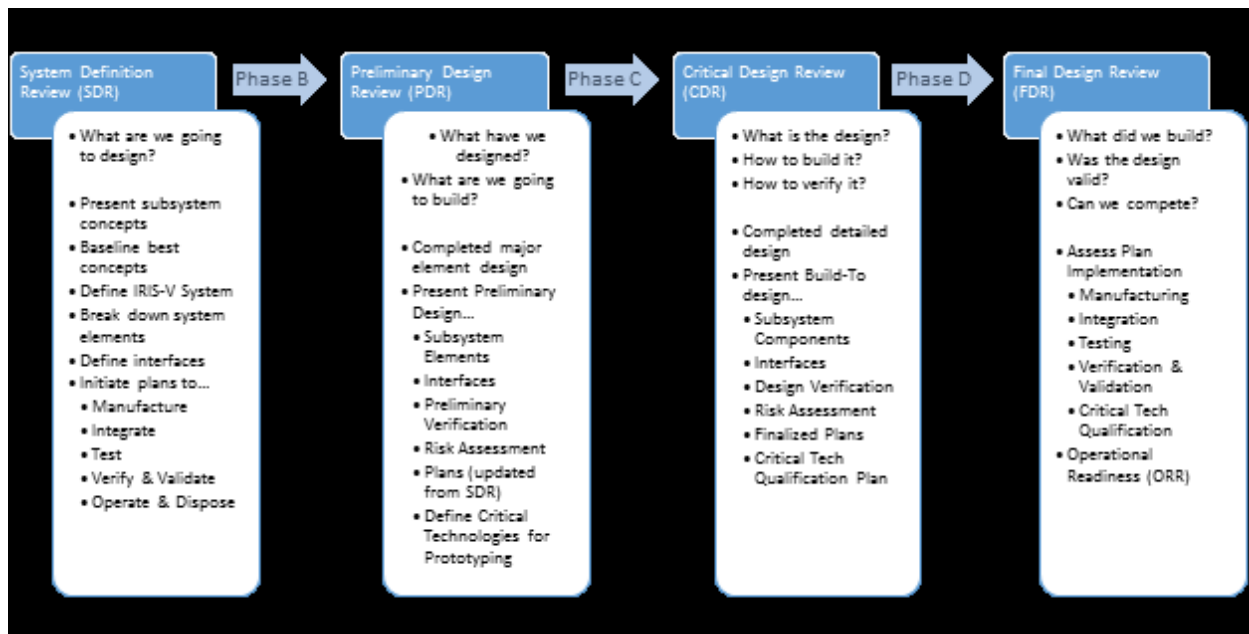


Figure 4: The RMC team from the University of Illinois at Urbana-Champaign outlines the importance of, the objectives of, and deliverables for their major reviews in their 2016 RMC Systems Engineering Paper.

Element III, Technical Merit: This element addresses key systems engineering artifacts. Specifically to be addressed in the paper are concept of operations, the system hierarchy, interfaces, requirements, technical performance budgeting and management, trade-off assessments, reliability, and verification of systems requirements. This element provides up to eight points for these eight required categories, with an additional six points that may be awarded for exceptional and/or additional category work (e.g., risk management, configuration management, functional analysis and decomposition, etc.) related to systems engineering technical merit for a total possible score of 14 points.

The system hierarchy is a central element in development of the system over the entire life cycle and should appear throughout a Systems Engineering Paper. RMC teams should discuss a system hierarchy that demonstrates that a decomposition process has been employed and is subsequently reflected in the major reviews and requirements derivations. Figure 5 shows the system hierarchy used by the John Brown University (John Brown University Eaglenaut Robotics, 2015) to develop their robot. This system hierarchy provided the backbone for requirements development and review hierarchy, as well as for their concept of operations.

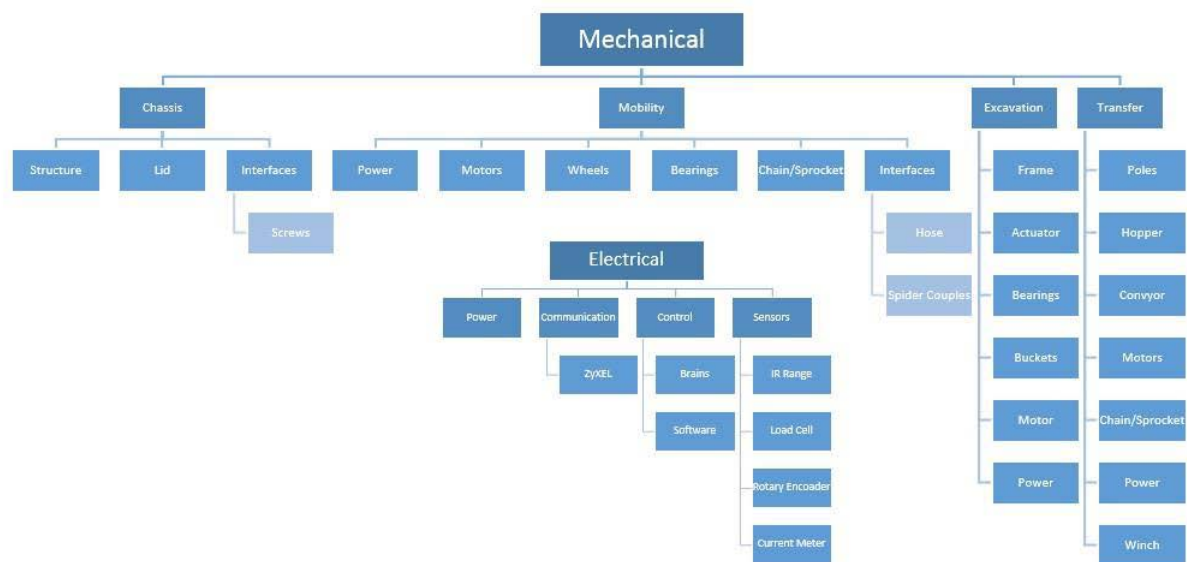


Figure 5: The 2015 Systems Engineering Paper from John Brown University presented a detailed system hierarchy that served as the backbone for their robot's design, development, and operation.

One challenge to RMC teams has been to understand that a concept of operations explains how the team will use the robotic system elements in the system hierarchy to accomplish the mission. In this case the mission is to excavate and collect the simulated regolith and simulated ice. The University of Illinois at Chicago team in their 2016 Systems Engineering Paper (Chicago EDT Robotics, 2106) presented a concept of operations that they used iteratively with their requirements and systems hierarchy to derive a system to perform well in the arena at the 2016 RMC. Figure 6 shows the top level of this concept of operations.

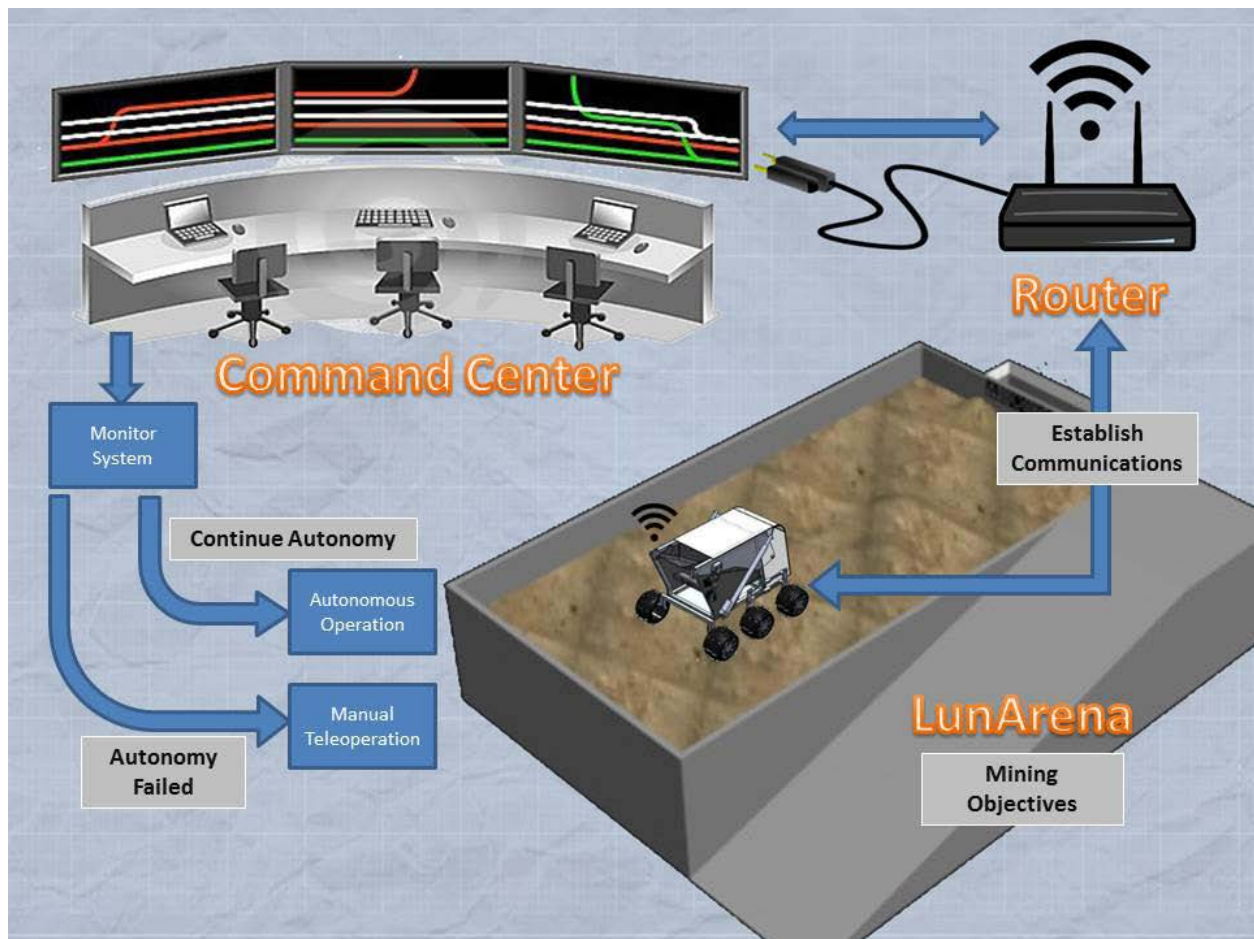


Figure 6: The University of Illinois at Chicago 2016 RMC team top level Concept of Operations.

The steps in operating the University of Illinois at Chicago robot system in figure 6 were as follows.

1. Place the robot into the mining arena.
2. Initialize the robot's power system boot-up sequence to establish network.
3. Initialize internal autonomous system data logging.
4. Traverse through the mining arena digging zone.
5. Mine a sufficient amount of regolith.
6. Return to starting point and dump the accumulated regolith on the assigned dumping bin.
7. Constantly determine the state of autonomy.
8. In the event that autonomy is determined to be no longer functional, switch over to manual tele-operation mode.
9. Repeat steps 4-9 until the round time limit has been reached.
10. Once the round time limit has been reached, confirm that all internal robot data logs have been properly saved.
11. Properly shut down the autonomy computers.
12. Disengage all power systems and remove robot from mining arena.

The use and understanding of the importance of trade-off assessments in making important system design decisions is exhibited by most RMC papers. Figure 7 is an example of an early trade-off assessment made by the 2016 Iowa State University RMC team (Iowa State University Cyclone Space Mining, 2016) to identify a suitable overall system concept.

Robot Design Decision Matrix:		RMC Max Scores					Long Term Mission Max Scores				
Measures	Weight	Scraper	Auger	Single HERMES	Multi HERMES		Weight	Scraper	Auger	Single HERMES	Multi HERMES
Mining Effectiveness (BP-1)	3	3	1	3	9		3	3	1	3	9
Mining Effectiveness (Icy Regolith)	9	1	9	1	1		9	3	3	3	9
Robot Weight Below 80kg	9	1	1	1	1		3	1	1	1	1
Weight-To-Effectiveness Ratio	9	1	3	9	9		9	1	3	9	9
Durability of Design	1	1	1	3	3		9	1	1	3	3
Limit Dust Production	3	9	3	3	3		3	9	3	3	3
Autonomy Capable	9	3	3	3	1		9	3	3	3	1
Design Risk	-3	3	9	1	3		-9	3	3	1	3
Weighted Score (TOTAL)		82	130	144	138			84	78	174	210
Percent of Max Score		57%	90%	100%	96%			40%	37%	83%	100%

Figure 7: The 2016 Iowa State University RMC team used a trade-off assessment early on in their project to select an overall robot design concept.

These are but a few of the excellent examples of surprisingly mature systems engineering as executed by the RMC teams each year.

Student and Faculty Advisor Support

The faculty advisor is a required member of each team. As discussed in the Content Element of the Systems Engineering Paper rubric, the faculty advisor is required to sign a statement that they reviewed and approve the Systems Engineering Paper. Students are further encouraged to require participation by their faculty advisor in all of their major reviews. Faculty advisors must also attend the on-site competition at the Kennedy Space Center in May.

At the on-site competition, the Lead Systems Engineering Judge hosts a Faculty Roundtable to discuss lessons learned and what NASA can do to help teams succeed, especially with the Systems Engineering Paper. It is not unusual for faculty advisors to invite some of their students to attend as well.

Also at the on-site competition, a Student Roundtable is held with the Systems Engineering Paper judges in attendance. This roundtable meeting is attended by students who are planning to compete in future competitions, and want to learn more about systems engineering as well as how to excel on the RMC Systems Engineering Paper. This roundtable meeting has been very well attended.

NASA provides a list of systems engineering references to all teams, and it includes sources from INCOSE.

Judging Process

The judging of the RMC Systems Engineering papers must be complete before the on-site competition begins. The Systems Engineering papers for each team are due in a final complete form about six weeks before the start of the on-site competition. This deadline forces the RMC teams to have completed their robot systems' designs, and to have verified them, in order to finish writing their Systems Engineering paper. Quite often, the designs that show up for the on-site competition will have design modifications that have resulted from the verification processes documented in the Systems Engineering Paper.

The Lead Systems Engineering Paper Judge recruits a team of NASA systems engineer volunteers to perform the evaluations. Judging of the RMC Systems Engineering Papers is a three pass process.

The first pass happens quickly with a small team of judges assessing each Systems Engineering Paper for whether content exists that addresses each of the required sub-elements in the rubric. This pass does not judge quality of the content, but attempts to assure that there is significant content for a panel of three judges to score the paper in the second pass. Student teams with Systems Engineering Papers that do not go forward to the second pass are provided a general critique and offered a detailed critique of their paper on a by request basis.

The second pass submits each Systems Engineering Paper that survived the first pass to at least three judges for initial scoring. Judges are invited to participate based on their knowledge and experience in systems engineering on NASA projects, and are provided with a set of judging guidelines. These judging guidelines help improve judging consistency. Teams of judges for each Systems Engineering Paper are selected to assure that no two judges judge together on multiple Systems Engineering Papers. This ameliorates judging styles, biases, and preferences from compounding in computation of Systems Engineering Paper average scores. All outlier scores are discussed for teams of judges on any particular Systems Engineering Paper, and overall score modifications usually result. Judges are required to provide comments justifying their scorings which helps tremendously in these discussions.

The third pass considers the top scoring set of Systems Engineering Papers that scored above a threshold established at the end of the second pass. A subset of judges read each of the papers that qualified for the third round and rank order this top scoring set of Systems Engineering Papers. A judges' conference is conducted to review and concur on the final rankings as well as for any awards to be presented.

Student teams with Systems Engineering Papers that do make it to the second pass are provided feedback and comments from three judges. Judges who support the RMC multiple years in a row often see returning teams make significant improvements in the subsequent year's Systems Engineering Paper scores and also in their robot's mining performance in the arena at KSC.

Award History

The two most important awards for the RMC are the Systems Engineering Paper award and the competition's grand prize, The Joe Kosmo Award of Excellence. The Systems Engineering Paper contributes 25% of the total score to determining the winners of The Joe Kosmo Award of Excellence. Table 4 lists the awardees from 2010-2016.

Table 4. Joe Kosmo Grand Prize and Systems Engineering Paper Awards 2010-2016.

Year	Joe Kosmo Award of Excellence	Systems Engineering Paper Awards
2010	Montana State University	Auburn University
2011	University of North Dakota	John Brown University
2012	1st: The University of Alabama in collaboration with Shelton State Community College 2nd: Iowa State University in collaboration with Wartburg College 3rd: West Virginia University	1st: Montana State University 2nd: John Brown University 3rd: University of Illinois at Urbana-Champaign
2013	1st: Iowa State University in collaboration with Nebraska Indian Community College & Wartburg College 2nd: West Virginia University in collaboration with Bluefield State College 3rd: The University of Alabama in collaboration with Shelton State College	1st: The University of Alabama in collaboration with Shelton State College 2nd: Military Institute of Science and Technology 3rd: John Brown University
2014	West Virginia University	1st: The University of Alabama 2nd: The University of Akron 3rd: The University of Illinois at Urbana-Champaign
2015	The University of Alabama in collaboration with Shelton State College	1st: The University of Illinois at Urbana-Champaign 2nd: The University of Alabama in collaboration with Shelton State College 3rd: John Brown University
2016	1st: The University of Alabama 2nd: Oakton Community College 3rd: Iowa State University	1st: The University of Illinois at Urbana-Champaign 2nd: Oakton Community College 3rd: The University of Alabama

A team that exemplifies how the Systems Engineering Paper judges' feedback improves a team's performance, both on the Paper and in the overall competition, is Oakton Community College. After participating for a few years, Oakton Community College was awarded an Honorable Mention for Most Improved Systems Engineering Paper in 2015. That was their first award in any segment of the Robotic Mining Competition. The following year, in 2016 (Table 4), Oakton Community College took second place in both the Systems Engineering Paper and Grand Prize awards. The students and faculty advisor revealed that it was their increased understanding and then adherence to good systems engineering practices that led to their success.

NASA has recognized that students with more experience applying systems engineering in their university/college careers are better prepared to enter the NASA workforce and be productive. In 2017, NASA RMC increased the relative importance of the Systems Engineering Paper score towards the Joe Kosmo Award of Excellence by increasing the percentage score contribution from 20% to 25%.

The 2017 NASA RMC Competitors

There are 53 teams that have registered for the 2017 NASA RMC. These teams come from universities and colleges in 27 states (including Alaska and Hawaii) and Puerto Rico. There are 47 teams that participated in the NASA RMC the previous year, and six that are new entrants. Since student teams are usually comprised of all classes, students who did not graduate the previous year and are on this year's team are carrying with them the lessons they learned from previous year's competitions. Student teams that continue competing in the NASA RMC demonstrate in their Systems Engineering Paper the process they used to assess and analyze their system's performance and robot system design in the previous competitions, and to develop their direction for the current year's competition.

These students, as a result of their previous participation in the NASA RMC, having experienced the complete life cycle for a technical project from ideation through decommissioning, will apply those lessons learned in the 2017 NASA RMC.

Summary and Conclusion

The NASA Robotic Mining Competition provides significant systems engineering educational opportunities for many undergraduate students, along with providing NASA with new ideas and concepts for how to remotely mine and collect Martian regolith. This competition requires that students be exposed first hand to the practical application of the systems engineering discipline in an intense time and budget constrained environment across the full life cycle, from ideation of a robot to actual operation of the robot in a reasonably realistic simulated Mars environment, to decommissioning of their system for the return home. This practical exposure and exercise of systems engineering will aid these students in their future careers.

Though there are a number of other university level engineering competitions besides the NASA RMC, the NASA RMC has a strong and required focus on the application of systems engineering. By including a Systems Engineering paper as a required component, other engineering competitions can enhance the experience for their student competitors.

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Biography

Jonette Stecklein is a member of NASA's Mars Study Capability Team performing Mars mission design assessments and architecture analysis. Her technical focus is defining and prioritizing the technology advancements needed to better implement future human spaceflight missions. Ms. Stecklein served as a judge for the inaugural NASA Lunabotics Competition in 2010, and has led the Robotic Mining Competition's Systems Engineering Judges Team since 2014. Ms. Stecklein holds a BS in Aerospace Engineering and an MS in Systems Engineering. She has served INCOSE since 1991 including as Chapter President, on the INCOSE Member Board, and on the INCOSE Board of Directors.

